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RESEARCH MEMORANDUM

HIGH MACH NUMBER, LOW-COWL-DRAG, EXTERNAL-COMPRESSION INLET WITH SUBSONIC DUMP DIFFUSER

By James F. Connors and Richard J. Flaherty

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

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A zero-cowl-drag, all-external-compression inlet with an abrupt area discontinuity or subsonic dump diffuser has been proposed and demonstrated for high Mach number application. Isentropic compression was focussed at the lip of a cylindrical cowl and limited by the requirements for shock attachment. Theoretical calculations of the performance of such an inlet showed that it may be suited for application at Mach numbers of 4 and above.

In an experimental investigation at Mach 3.85, a 4.75-inch-diameter inlet attained a total-pressure recovery of 0.~~41~~ at a corresponding mass-flow ratio of 0.92. Subsonic diffusion over an area ratio of about 3.5 to 1.0 was accomplished in 1.25 inlet diameters. Essentially no difference in performance was obtained in a comparison of the dump and a conventional subsonic diffuser. On a range basis, the over-all performance of this inlet was at least comparable with that of the best on-design isentropic external-compression inlet previously reported.

A variable Mach number configuration utilizing a telescoping spike with a subsonic dump diffuser is also included.

Author

INTRODUCTION

In the over-all evaluation of a particular inlet, internal performance must be assessed in the light of its respective costs in drag, weight, and mechanical complexity. This is especially true for inlets at speeds above Mach 3, where the need for maintaining low external drag and for using variable geometry to accommodate variable-Mach-number operation is generally accepted.

All-external-compression inlets in achieving high internal performance (ref. 1) are generally penalized by cowl drags which represent a significant portion of the net engine thrust (e.g., in ref. 2, cowl drags

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alone accounted for 10 to 20 percent of engine thrust at Mach 3). The all-internal-compression inlet (ref. 3), on the other hand, achieves high pressure recoveries with virtually no cowl drag, but requires rather long gradual compression surfaces which, in the axisymmetric case, may require spike-translation distances of 2 to 3 inlet diameters. Also, in contrast to the external-compression type, the internal-compression inlet appears to be limited to supercritical or critical operation because of the severe discontinuity in performance with expelled-shock operation. A combination external-plus-internal-compression inlet (ref. 4) has recently shown a very high over-all performance at Mach 3.0. This inlet, in addition, requires only a relatively small amount of spike translation and has a rather short over-all length. 4638

In the present study, the external-compression inlet was examined further from the viewpoint of achieving a short zero-cowl-drag configuration for operation at a Mach number of 3.85. First considerations were based solely on a fixed Mach number design. A cylindrical cowl was used with isentropic all-external compression focussed at the lip and limited by the requirements for shock attachment on the cowl. The over-all configuration employed an abrupt area discontinuity, or dump, instead of the conventional subsonic diffuser. This design approach possesses the potential advantages of a short over-all length and correspondingly low weight.

In order to evaluate such an approach to high Mach number inlet design, an experimental investigation was conducted on a small-scale model at a Mach number of 3.85. Internal performance (i.e., total-pressure recovery and mass-flow ratio) was determined for a limited range of spike tip projections and angles of attack. Surveys of the internal flow were made at several axial stations to determine effective subsonic diffuser lengths.

Based on the results of this present study, the theoretical performance of this type of inlet was analyzed for a wide range of Mach numbers to put it in the proper perspective with relation to other supersonic inlet types. To accommodate variable Mach number operation, a variable-geometry-inlet proposal, utilizing the principle of the subsonic dump diffuser at high Mach numbers in combination with a telescoping spike is also included.

SYMBOLS

The following symbols are used in this report:

A_{in} inlet capture area, sq ft

A_3 diffuser-exit flow area, sq ft

M	Mach number
m_3/m_0	inlet mass-flow ratio, $\rho_3 A_3 V_3/\rho_0 A_{in} V_0$
P	total pressure, lb/sq ft
$\overline{P}_3/P_0$	total-pressure recovery
p	static pressure, lb/sq ft
q	dynamic pressure, lb/sq ft
V	air velocity, ft/sec
x	distance, in.
α	angle of attack, deg
θ_l	cowl-position parameter, angle between axis of symmetry and line from spike tip to cowl lip, deg
ρ	density of air, lb/cu ft

Subscripts:

l	lip
0	conditions in free stream
3	conditions at diffuser exit

Superscript:

—	area-weighted value

DESIGN CONSIDERATIONS

The inlet configuration studied herein utilized a cylindrical cowl with all-external isentropic compression that was focussed at the lip and limited by the requirements for shock attachment on the cowl. At Mach 4.0, the theoretical Mach numbers behind the terminal shock are only about 0.5. The corresponding dynamic head is relatively small. In fact, by assuming a complete loss of this dynamic head, which might happen in the mixing processes involved in dumping the flow, little effect on kinetic-energy efficiency would result. For example, at Mach 4.0 a pressure recovery of 0.54, or a kinetic-energy efficiency of 0.95, might be possible with no turning loss and an ideal subsonic diffuser; whereas a pressure recovery of 0.46, or a kinetic-energy efficiency of 0.93, would be available if the flow were simply dumped through an abrupt area discontinuity and complete mixing losses accepted. This latter case corresponds to a recovery merely of the static pressure behind the terminal shock. Actually, based on the work of reference 5, it might be anticipated that as much as 75 percent of the dynamic head could be recovered by the dump diffuser with adequate provisions for boundary-layer control.

In a theoretical study of all-external-compression inlets with zero-drag cowls and constant-area throat sections (ref. 6), the losses involved in simply turning the flow back to the axial direction after supersonic compression were analyzed. At a free-stream Mach number of 4.0, this turning loss was computed to be as high as 20 percent of the theoretical inlet pressure recovery. This loss is somewhat greater than the 17.4-percent loss calculated for a subsonic dump diffuser by assuming the inlet could recover only the static pressure behind the normal shock. The significant point to be made here is that the turning loss and the dump loss are of the same order of magnitude. From an application viewpoint, the potential short-length low-weight advantages of the dump arrangement are obvious. A further refinement that might be incorporated advantageously in the design of such a diffuser is the trapped-vortex concept which, in effect, provides a sort of aerodynamic diffuser. This scheme has been successfully demonstrated by a number of investigators, for example, in reference 7.

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In order to explore the feasibility of these elements being incorporated into an actual supersonic-inlet configuration, an inlet was designed and evaluated experimentally at a Mach number of 3.85.

APPARATUS AND PROCEDURE

The experimental investigation was conducted in the Lewis 2- by 2-foot supersonic wind tunnel at a Mach number of 3.85. A schematic drawing of the over-all inlet test model is shown in figure 1(a). The model was sting mounted off the tunnel walls and had a movable exit plug to vary the back pressure on the inlet. Only internal performance was considered. Based on the cowl-lip diameter (4.75 in.), the Reynolds number was constant at 0.41×10^{6}.

Details of the inlet geometry are shown in the drawings of figures 1(b) and (c) and in the photographs of figure 1(d). The spike was designed for isentropic compression, focussed at the cowl lip according to the method of reference 1. The cowl consisted of a cylindrical internal surface with a 5° external lip angle. Limited by the requirements for attached shocks on this cowl, the isentropic compression reduced the flow Mach number from the free-stream value of 3.85 to a value of 2.4 at the entrance. By assuming the inlet would yield only the recovery of the static pressure behind a normal shock at Mach 2.4, the theoretical recovery would be 0.46. With an ideal subsonic diffuser the theoretical recovery is 0.52.

For boundary-layer control a rearward-facing variable-gap flush slot was employed in the throat. For all the data, shown herein, the bleed gap was set at 0.140 inch. Bleed air was passed through a hollow sting and, from there, aspirated to the free stream through two hollow support struts. The function of this bleed was to avoid or minimize the effects of pressure feedback from the terminal shock. The base area of the step section was undercut to an arbitrary radius in order to effect a vortex trap. As indicated in figure 1(a), a wooden block simulating a conventional subsonic diffuser with an over-all equivalent conical area expansion of 6° was also used for comparison purposes in order to determine the effects of dumping.

Total-pressure recovery was based on the average of 24 tubes at a station 18.82 inches from the cowl lip. Mass-flow ratio was computed from the measured static pressure at station 18.82, a calibrated sonic-discharge area at station 25.75, and the assumption of one-dimensional isentropic flow. At various longitudinal stations along the diffuser, additional survey rakes and static-pressure orifices were installed along the duct to define the lengths required for effective subsonic diffusion.

Data were recorded for several values of tip projection and angles of attack up to 8°. A dynamic pressure pickup was installed at a station 7.13 inches from the cowl lip to check any pressure fluctuations that might develop from local turbulence created in the dumping process. These measurements were made only at zero angle of attack with both the dump and conventional subsonic diffusers.

RESULTS AND DISCUSSION

Diffuser performance characteristics are presented in figure 2 for zero angle of attack and two different tip projections. All data, reported herein, were obtained with roughness (a 1/2-in. band of No. 100 Carborundum grit) applied to the spike tip to force an initial turbulent boundary layer and, thereby, to avoid laminar separation difficulties. Without roughness, the performance was somewhat lower. For all data reported, the bleed gap in the throat was set at 0.140 inch. Without bleed, the total-pressure recovery was only 0.30 to 0.32. Apparently, boundary-layer control is required to handle pressure feedback from the terminal shock system. At the design value of θ_l ($17^{\circ}2.5'$), both the dump and the conventional subsonic diffusers had essentially the same internal performance with maximum subcritical recoveries of 0.475 and 0.50, respectively. However, the corresponding mass-flow ratio was rather low, approximately 0.7. Critical recovery and mass-flow ratio were approximately 0.39 and 0.85, respectively. Dynamic pressure measurements at station 7.13 inches from the cowl lip indicated no difference in the level of flow fluctuation with the dump as compared with that using the conventional diffuser.

By retracting the spike 1/16 of an inch to a θ_l of 17°10', the supercritical mass-flow ratio was increased to 0.92 with a critical recovery of approximately 0.41. Stable subcritical operation of the inlet was realized down to a mass-flow ratio of about 0.7 with little change in recovery level.

To place this inlet in its proper perspective with relation to other configurations, it can be pointed out that its internal performance (recovery, 0.41; mass-flow ratio, 0.92) was about the same as that attained with the conventional on-design two-cone inlet reported in reference 8. Similarly, an on-design isentropic inlet at a Mach number of 3.85 gave a 0.57 recovery, but with an attendant cowl-pressure drag. Approximate calculations were made to compare the over-all performance of these inlets on a maximum-range basis. It was assumed that the additive drags were the same for both inlets since their capture mass flows were equal. The experimental cowl-pressure drag was given in reference 8 for the high-recovery inlet. The configuration of this study with its essentially zero-cowl-pressure drag and subsonic dump arrangement was at least comparable with the on-design isentropic inlet of reference 8.

A schlieren photograph of the supercritical inlet airflow pattern for a θ_l of 17°2.5' is shown in figure 3. At zero angle of attack the compression waves appear to focus somewhat ahead of the cowl lip, thus indicating some flow spillage. At the spike tip, the grit or roughness applied here as an artificial boundary-layer trip may be seen. The boundary layer along the contoured spike appears well behaved with no indications of separation. At the 17°10' value of θ_l, the spillage around the cowl lip was diminished, but little change in flow pattern was noted.

Static-pressure distributions along the subsonic duct at zero angle of attack and a θ_l of 17°2.5' are presented in figure 4 for several values of total-pressure recovery. For the most part, the static-pressure rise in the dump diffuser had been accomplished in approximately 1.25 inlet diameters (5.94 in. from the cowl lip). As indicated by these data, the normal-shock pressure rise is spread out over a considerable distance, and there appears to be no sharp rise, such as theoretically considered through a single finite terminal shock. In theory, a pressure rise (p/P_0) to 0.46 was anticipated. Total-pressure profiles at various axial stations are shown in figure 5 for three different recovery levels, corresponding to supercritical, approximately critical, and subcritical operating conditions. The data at station 7.13 inches (1.5 inlet diam) downstream of the cowl lip indicated no separation at any point across the entire duct annulus for all three conditions. At critical, the distortion level is extremely low at this station. As the inlet became subcritical, there was a reversal in trend in that the high-energy air, indicated by the peak in the profiles, shifted from near the outer shell towards the sting. However, the profile at station 7.13 was still quite flat.

The effects of angle of attack on internal performance are indicated in figure 6. As is generally typical of axisymmetric inlets, total-pressure recovery and mass-flow ratio decreased moderately with angles up to 8°, and the recovery was approximately 0.30.

Calculations were made to estimate the pressure-recovery potential of isentropic zero-cowl-drag inlets with subsonic dump diffusers over a wide range of supersonic Mach numbers. The results are presented in figure 7. The cross-hatched band indicates the theoretical recovery for isentropic all-external compression carried to the limit of shock attachment on a cylindrical cowl. The upper boundary shows the level of performance possible with an ideal (no loss) subsonic diffuser, while the lower boundary represents that for full dumping loss or a recovery of only the static pressure behind the terminal shock. As shown in figure 7, the results of the present exploratory study fall close to and somewhat below the lower boundary. For comparison purposes, lines corresponding to normal-shock recovery and the theoretical all-external-compression limit of reference 1 are also included. The isentropic zero-drag-cowl inlet with subsonic dump appears quite competitive at the higher Mach numbers (4.0 and above). This, of course, is because of the low subsonic Mach numbers in the throat. As free-stream Mach number decreases, this subsonic throat Mach number increases, and the feasibility of dumping and accepting a high mixing loss diminishes rather rapidly. For example, at Mach 2.0 a complete loss of the subsonic dynamic pressure q would result in less than normal-shock recovery.

An extension of the dump prinicple to a variable-geometry inlet capable of operating over a wide range of Mach numbers is illustrated in figure 8. To approximate the theoretical variation in isentropic surface contour with free-stream Mach number, a telescoping spike (ref. 9) was assumed. At the higher Mach number conditions, a dumping arrangement as shown in figure 8(b) was used. As the Mach number decreases, the shoulder or throat elements of the telescoping centerbody are successively retracted into the subsonic diffuser, thus increasing the throat area. In the retracted positions, the flow goes through, as well as around, the rings. At the same time, the elements of the spike translate relative to each other to form an envelope contour for isentropic focussed compression corresponding to each Mach number. The cowl or the entire centerbody also translates to keep the lip at the focal point. For all settings of the spike, boundary-layer control can be maintained at the inlet throat, as was done in the present study. For the low Mach number configuration, the geometry of a somewhat conventional subsonic diffuser is approached.

The obvious disadvantage to such a scheme might be complexity. However, it should be possible in an actual full-scale version to design some type of cam or variable-pitch-screw arrangement to program these telescoping elements with the Mach number. The dumping provisions at high speeds, of course, tend towards weight savings. Against such mechanical problems must be weighed the potential aerodynamic performance of such an inlet.

CONCLUDING REMARKS

A zero-cowl-drag, all-external-compression inlet with a subsonic dump diffuser has been investigated at Mach 3.85. This inlet had an isentropic spike with compression focussed at the lip of a cylindrical cowl and limited by the requirements for shock attachment. An abrupt area discontinuity, or dump, was used instead of the conventional subsonic diffuser. At Mach 3.85 a pressure recovery of 0.41 and a mass-flow ratio of 0.92 were obtained with this dump diffuser. Subsonic diffusion over an area ratio of about 3.5 to 1.0 was accomplished in 1.25 inlet diameters. Essentially no difference in performance was obtained in a comparison of dump and conventional subsonic diffusers.

The results of this study substantiate the feasibility of utilizing the dump principle for high Mach number inlet application. The dump principle may be best suited for use at Mach numbers of 4 and higher. Further study with larger scale models appears desirable to evaluate any viscous effects upon performance. With this type of inlet it might be expected that the small scale models of the present study would be more sensitive to the adverse effects of shock-boundary-layer interaction and the strong mixing processes inherent in such a flow system.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 13, 1958

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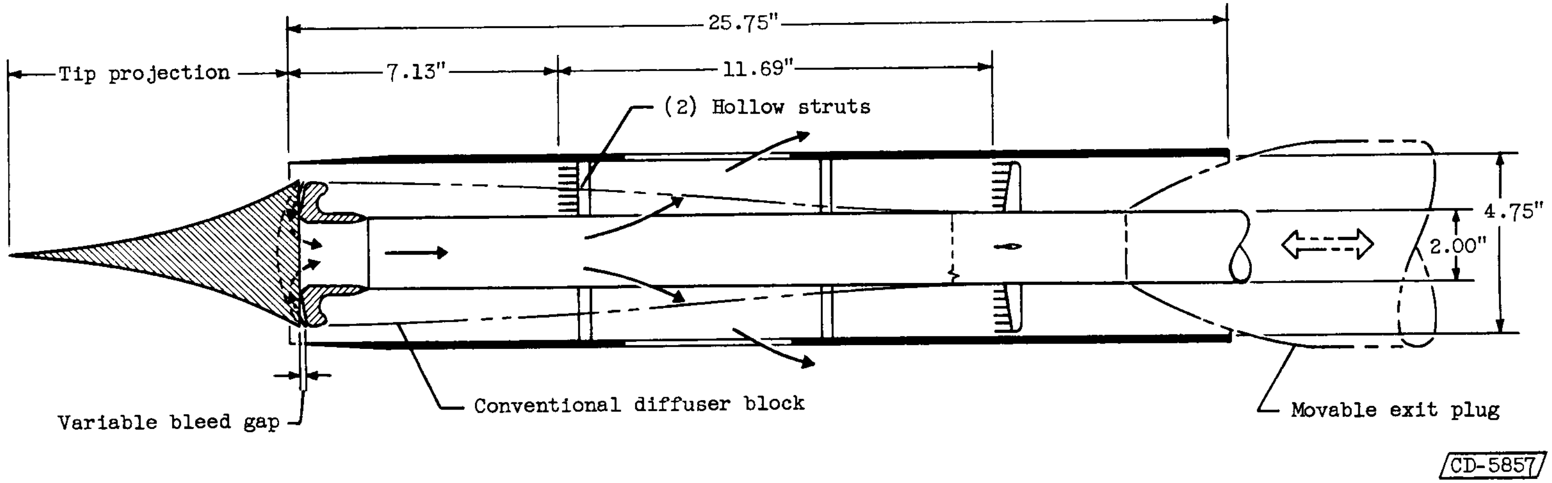

(a) Schematic view of over-all test model.

Figure 1. - Experimental apparatus.

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X ±0.005	Y_{Rad} ±0.002
0	0
.500	.070
1.000	.140
1.500	.215
2.000	.280
2.500	.355
3.000	.440
3.500	.535
4.000	.635
4.500	.745
5.000	.860
5.250	.925
5.500	1.000
5.750	1.075
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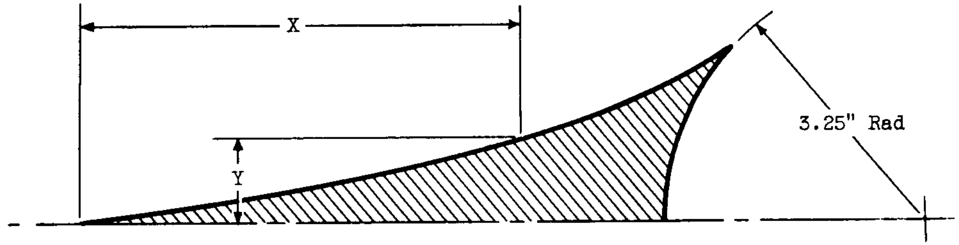
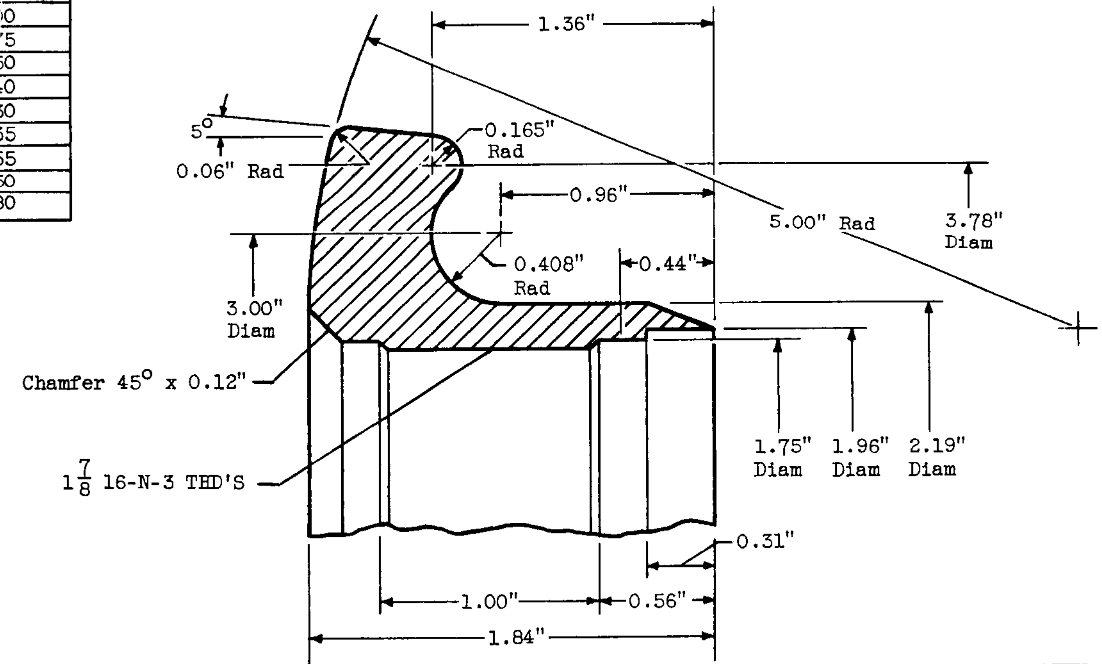


(b) Spike details.



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(c) Aft-spike details.

Figure 1. - Continued. Experimental apparatus.

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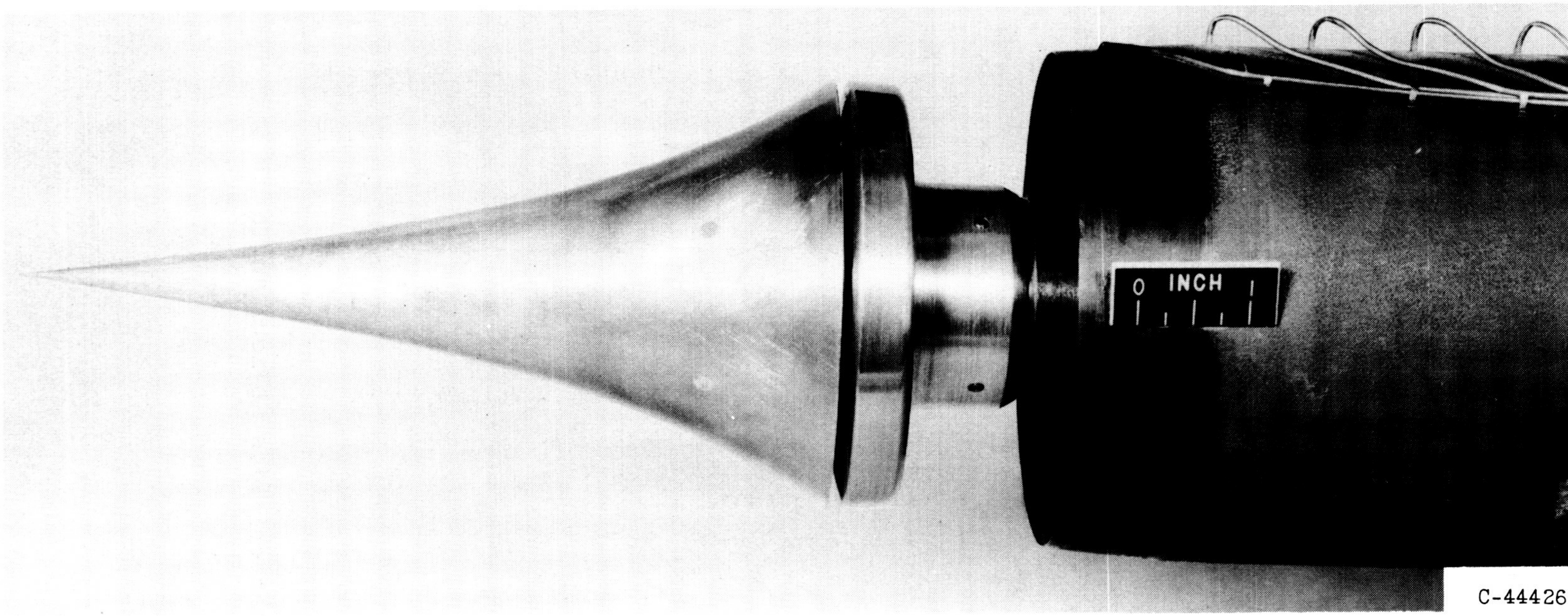
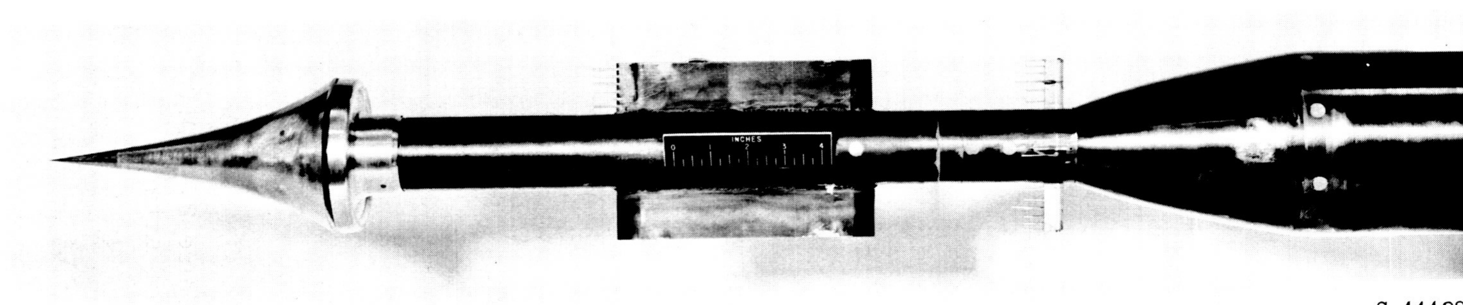


Centerbody with cowl pulled back.



Test model with outer shell removed.

(d) Photographs of isentropic-spike, dump-diffuser-inlet test model.

Figure 1. - Concluded. Experimental apparatus.

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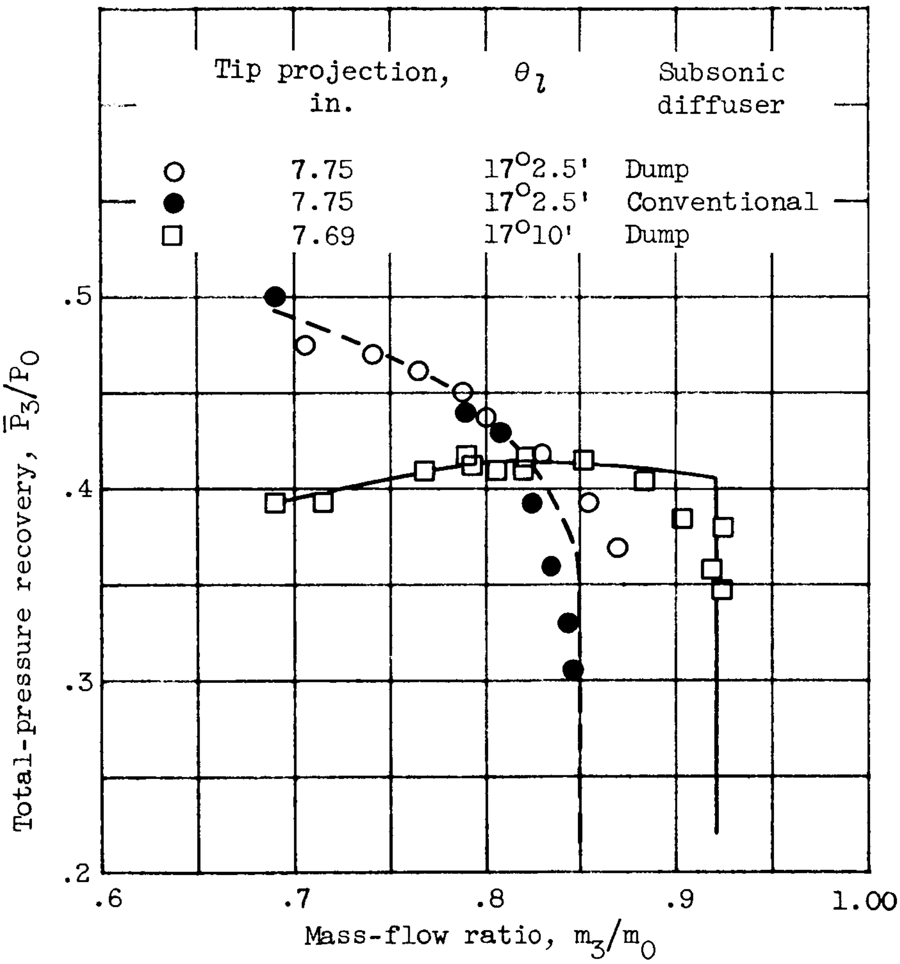

Figure 2. - Diffuser characteristics at zero angle of attack.

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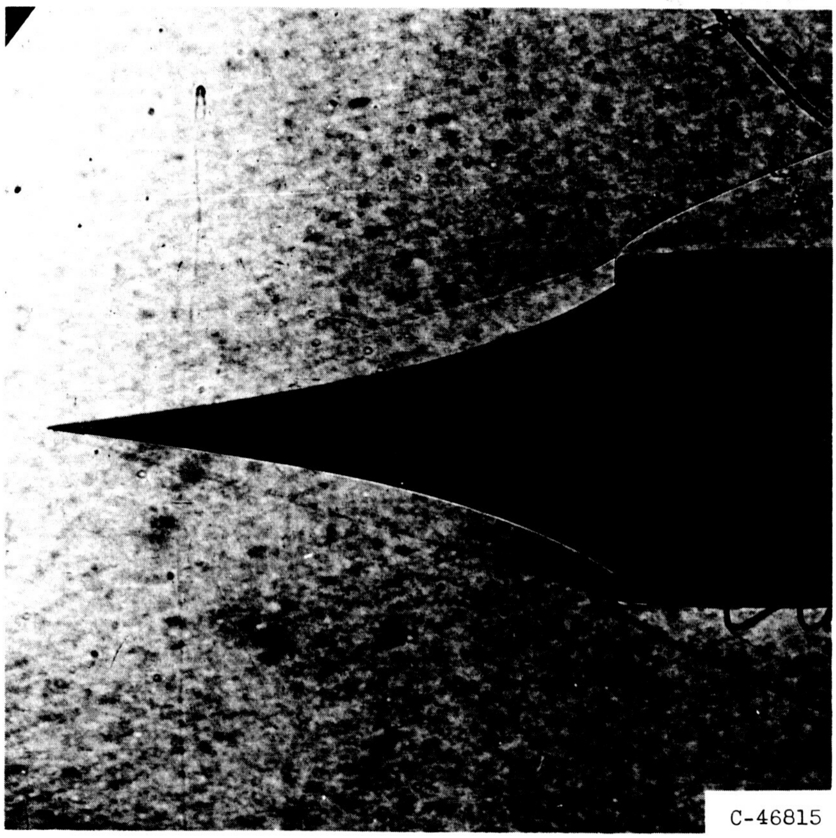

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Figure 3. - Inlet airflow pattern at zero angle of attack.

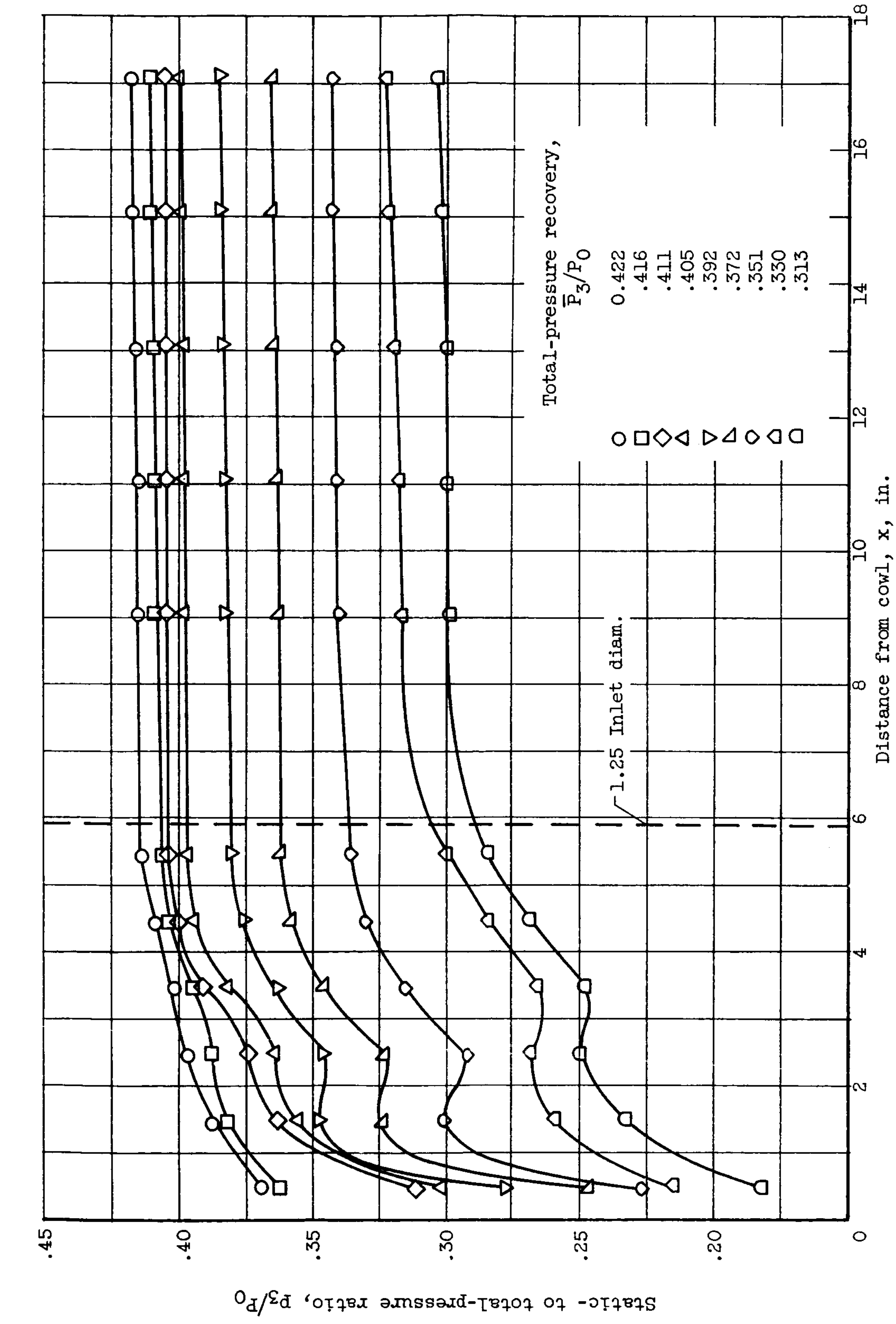

Figure 4. - Static-pressure distributions along the duct. Zero angle of attack; cowl-position parameter, $17^{o}2.5'$.

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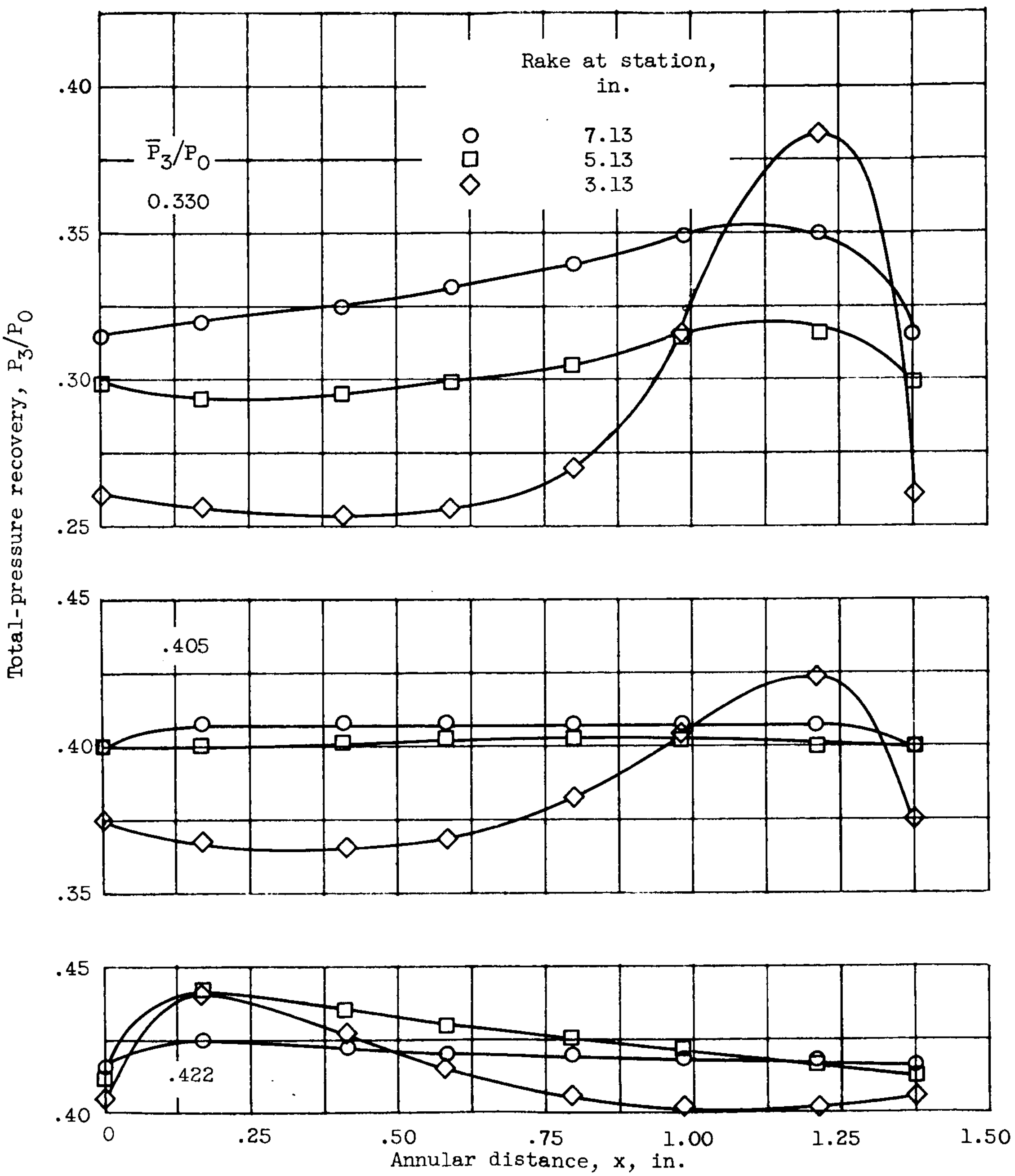

Figure 5. - Total-pressure profiles at various axial stations. Zero angle of attack; cowl-position parameter, 17°2.5'.

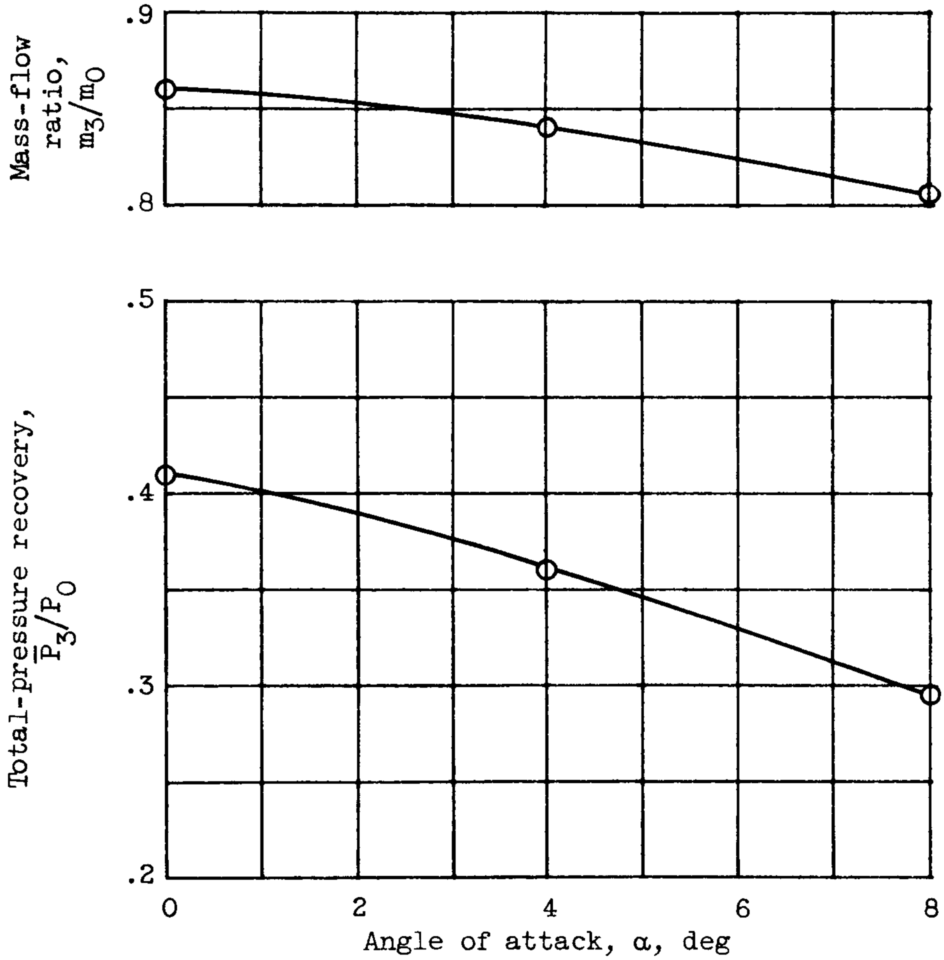

Figure 6. - Effect of angle of attack on internal performance. Cowl-position parameter, $17^{o}2.5'$.

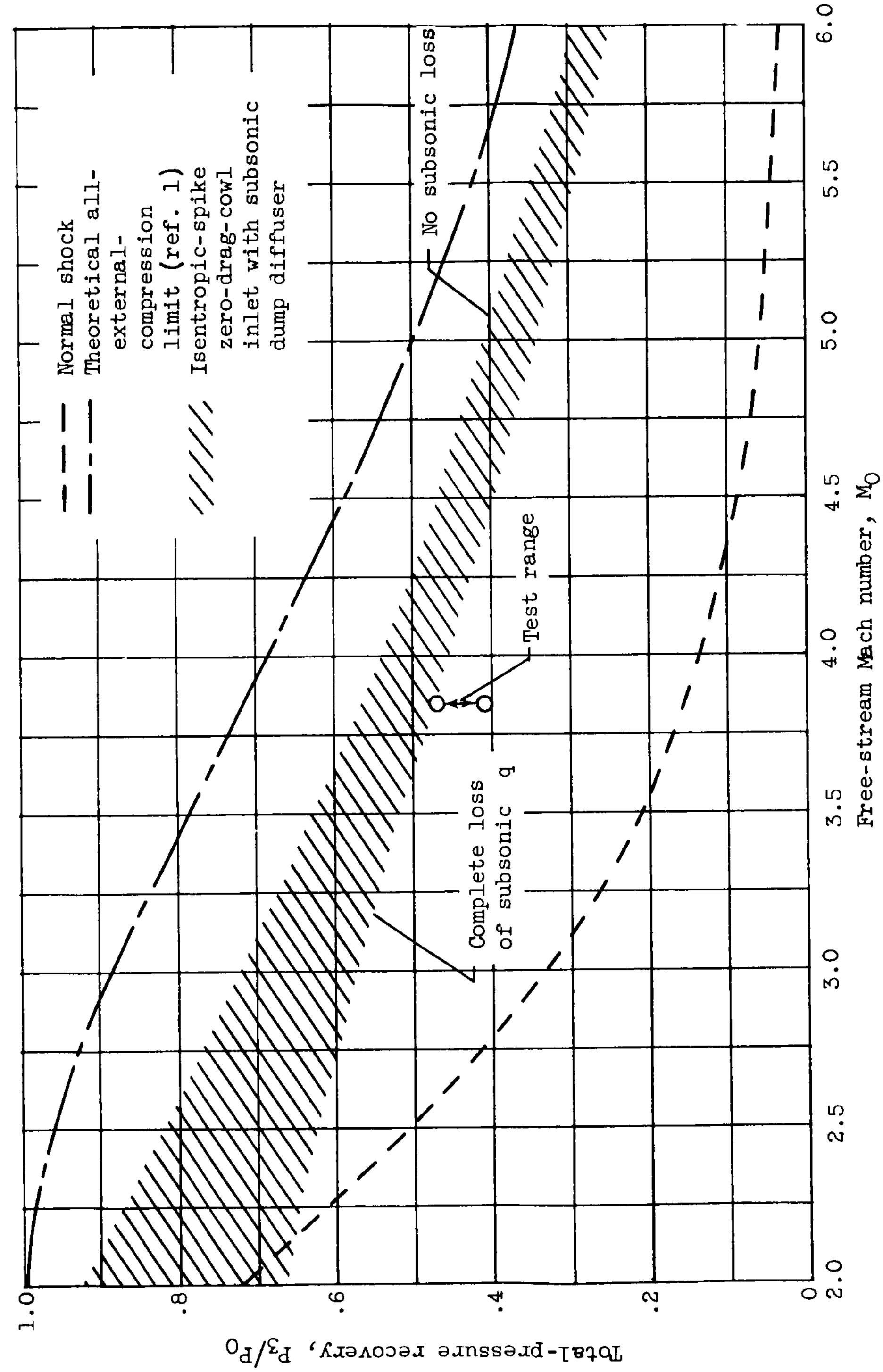

Figure 7. - Variation with Mach number of the performance of an isentropic-spike zero-drag-cowl with subsonic dump diffuser.

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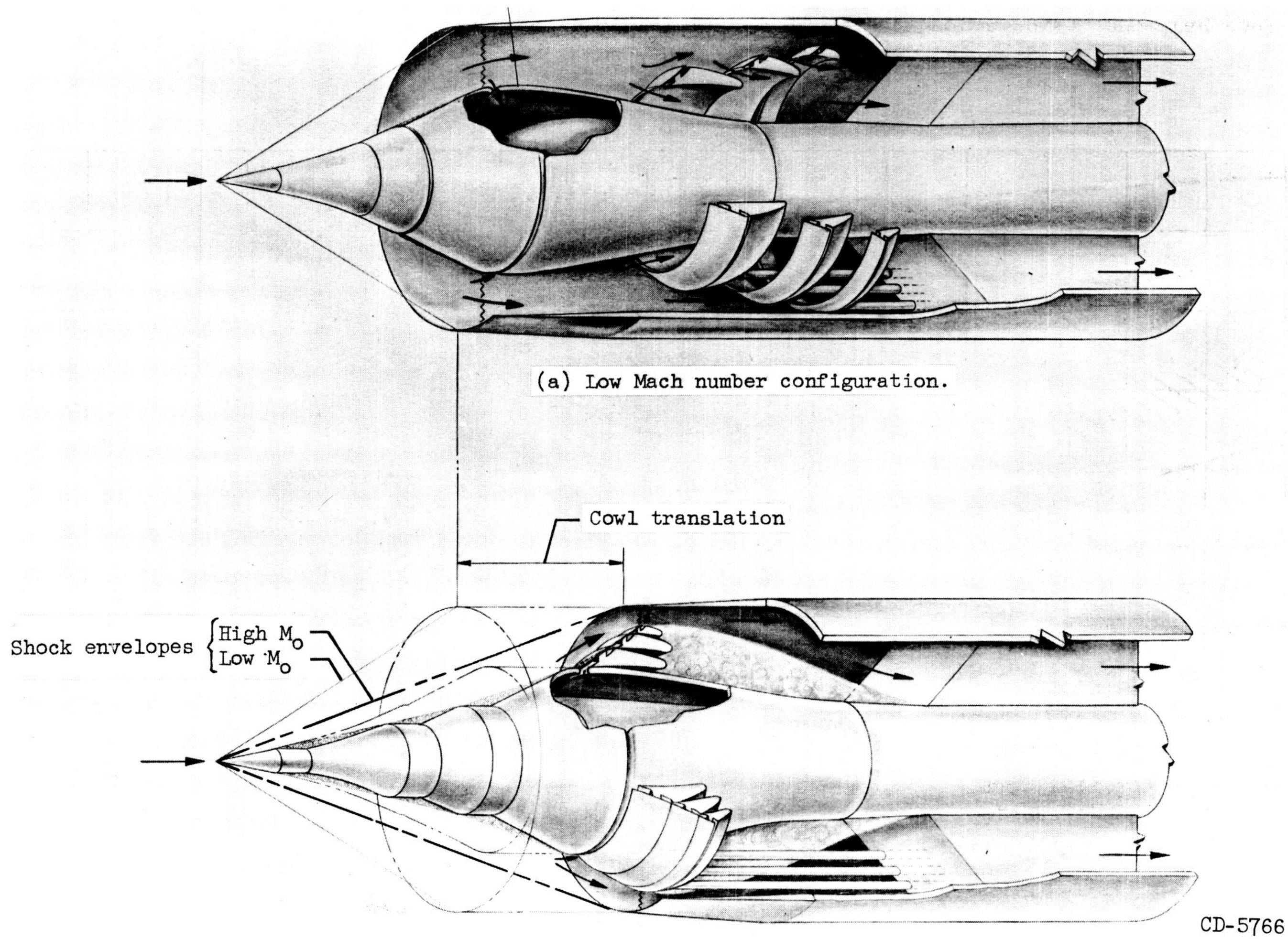

(b) High Mach number configuration with dump diffuser.

Figure 8. - Zero-drag-cowl, telescoping-spike inlet with subsonic dump diffuser for variable Mach number operation.

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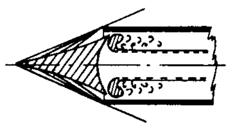
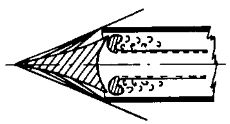
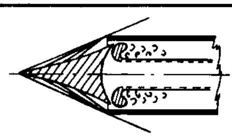
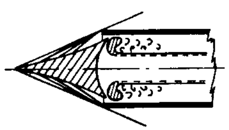
NOTES: (1) Reynolds number is based on the diameter of a circle with the same area as that of the capture area of the inlet.

(2) The symbol * denotes the occurrence of buzz.

Report and facility	Description			Test parameters				Test data				Performance		Remarks
	Configuration	Number of oblique shocks	Type of boundary-layer control	Free-stream Mach number	Reynolds number $\times 10^{-6}$	Angle of attack, deg	Angle of yaw, deg	Drag	Inlet-flow profile	Discharge-flow profile	Flow picture	Maximum total-pressure recovery	Mass-flow ratio	
CONFID. RM E58A09 Lewis 10- by 10-ft unitary wind tunnel	 Axisymmetric low-drag external-compression inlet with subsonic "dump"	∞ (Isen-tropic)	Throat flush slot	3.85	0.41	0 to 6	0		✓	✓	✓	0.47 to 0.41	0.71 to 0.92	Essentially zero-cowl-lip drag, short subsonic dump diffuser. Most suitable for high Mach number applications (above M = 4).
CONFID. RM E58A09 Lewis 10- by 10-ft unitary wind tunnel	 Axisymmetric low-drag external-compression inlet with subsonic "dump"	∞ (Isen-tropic)	Throat flush slot	3.85	0.41	0 to 6	0		✓	✓	✓	0.47 to 0.41	0.71 to 0.92	Essentially zero-cowl-lip drag, short subsonic dump diffuser. Most suitable for high Mach number applications (above M = 4).
CONFID. RM E58A09 Lewis 10- by 10-ft unitary wind tunnel	 Axisymmetric low-drag external-compression inlet with subsonic "dump"	∞ (Isen-tropic)	Throat flush slot	3.85	0.41	0 to 6	0		✓	✓	✓	0.47 to 0.41	0.71 to 0.92	Essentially zero-cowl-lip drag, short subsonic dump diffuser. Most suitable for high Mach number applications (above M = 4).
CONFID. RM E58A09 Lewis 10- by 10-ft unitary wind tunnel	 Axisymmetric low-drag external-compression inlet with subsonic "dump"	∞ (Isen-tropic)	Throat flush slot	3.85	0.41	0 to 6	0		✓	✓	✓	0.47 to 0.41	0.71 to 0.92	Essentially zero-cowl-lip drag, short subsonic dump diffuser. Most suitable for high Mach number applications (above M = 4).

Bibliography

These strips are provided for the convenience of the reader and can be removed from this report to compile a bibliography of NACA inlet reports. This page is being added only to inlet reports and is on a trial basis.

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